A geology-based 3D seismic velocity model of Canterbury, New Zealand

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ABSTRACT: This paper presents a seismic velocity model of Canterbury, New Zealand based on 3D geologic surfaces and velocities from a range of data sources. The model provides the 3D crustal structure in the region at multiple length scales for seismic wave propagation simulations, such as broadband ground motion and shallow site response analyses related to understanding the ground motions and site responses during the 2010-2011 Canterbury earthquakes. Pre-Quaternary geologic horizons are calculated based on the reinterpretation of a comprehensive network of seismic reflection surveys from seven different campaigns over the past 50 years, as well as point constraints across an array of petroleum industry drill holes. Particular attention is given to a detailed representation of Quaternary stratigraphy, representing shallow (z<250m) near-surface layers in the model. Seismic velocities are obtained from seismic reflection processing (for V_P) and also recently performed active and passive surface wave analyses (for V_S). Over 1,700 water wells in the region are used to constrain the complex inter-bedded Quaternary stratigraphy (gravels, sands, silts, organics etc.) near the coastline, including beneath urban Christchurch, which has resulted from fluvial deposition and marine regression and transgression. For the near-surface Springston and Christchurch Formations in the Christchurch urban area (z<50m), high-spatial resolution seismic velocities (including V_{S30}) were obtained from over 13,000 cone penetration tests combined with a recently developed CPT-V_S correlation.

1 INTRODUCTION

The 2010-2011 Canterbury earthquake sequence produced severe ground motions which caused significant ground failure and structural damage in Christchurch city and its surrounding suburbs. A large number of ground motions from these earthquakes were recorded due to a dense array of strong motion instruments over the Canterbury plains, producing a dataset which exhibits numerous ground motion phenomena such as rupture directivity, basin-generated waves, basin edge effects, and nonlinear surficial soil response (Bradley, 2012; Bradley and Cubrinovski, 2011). Such observations provide an unparalleled opportunity for new ground motion understanding. However, although empirical ground motion prediction equations (GMPEs) allow for a comparison of these ground motions, they provide little insight into the underlying physics of these observations. Hybrid broadband ground motion simulation (e.g. Graves and Pitarka, 2010) is a physics-based approach which can produce synthetic ground motions that properly represent the complex geology within a region providing an opportunity to fundamentally understand the salient features of the ground motion phenomena. Such simulations require a realistic 3D seismic velocity model as a domain for the numerical solution of the seismic wave propagation equations.

In this paper, a seismic velocity model for hybrid broadband ground motion simulation of the 2010-2011 Canterbury earthquakes is presented based on 3D geologic surfaces and velocities. The Canterbury Velocity Model (CVM) represents the 3D variation of P- and S-wave velocity and density (V_p, V_s and ρ) of the Canterbury region and hence must sufficiently represent the critical aspects of the crustal structure over multiple length scales. As a result, numerous sources of data are utilized in the model formulation to provide adequate resolution where necessary.

An overview of the velocity model data sources and geologic units considered is firstly presented. The development of geologic surfaces for the pre- and post-Quaternary are then discussed separately. Finally, the specification of velocity variations within each geologic unit is then discussed.

2 VELOCITY MODEL OVERVIEW

The velocity model adopts a geologic surface-based methodology in which 3D surfaces are utilized to define the boundaries of different geological units which subsequently have different geophysical (e.g. P-, S-wave velocities and densities) and geotechnical properties. The geologic units considered are shown in Figure 1. The Quaternary geology is characterized in finer detail to ensure the spatial complexities and inter-bedded nature, which are expected to be important in high-frequency ground motion simulation are adequately modelled. Rules used to prescribe material properties include linear and 3D interpolation in space as guided by the experimental data relevant to the grid point in the velocity model. Thus, for each (Lat,Lon,Depth) point at which the model properties are required, the relevant bounding 3D surfaces are first determined, and then the appropriate rule-based model utilized to compute V_p, V_s and ρ. The model domain is currently a rectangular area between Lat = [-43.2˚,-44.0˚], and Lon = [171.5˚, 173.0˚], and extends to a depth of 50km below sea level. This essentially spans the area between the foot of the Southern Alps in the North West to Banks Peninsula in the East as shown in subsequent figures.

CVM Unit	Period	Epoch	Waipara	Ashley	Christchurch	South Rakaia
Quaternary	Quaternary	Holocene Pleistocene	Canterbury gravels			
Pliocene	Neogene	Pliocene	Kowai Fm.			
Upper Miocene		Miocene	Tokama Siltstone/Mt Brown Fm.	Undiff	Undiff	Tokama Siltstone
Miocene Volcanics			Not present	Starvation Hill Basalts	Banks Peninsula Vol. Group	Undiff
Lower Miocene			Waikari Fm.	Undiff	Undiff	Waikari Fm.
Paleogene	Paleogene	Oligocene	Amuri Limestone			
		Eocene	Homebush Sandstone			
			Ashley Mudstone		View Hill Vol. Group	Ashley Mudstone
			Waipara Greensand Fm.			
		Paleocene	Loburn Mudstone	Not Present		Loburn Mudstone
Late Cretaceous	Cretaceous	Late	Conway/Broken River Fm.		Conway/Broken River Fm.	
					Mt Somers Vol. Group	
Basement	Jurassic/ Triassic	Torlesse composite terrain (Greywackes)				

Period	Christchurch
Holocene	Springston Fm.
	Christchurch Fm.
Pleistocene	Riccarton Gravels
	Bromley Fm.
	Linwood Gravels
	Heathcote Fm.
	Burwood Gravels
	Shirley Fm.
	Wainoni Gravels
	Undiff

Figure 1. Modelled geologic units in the Canterbury Velocity Model (CVM).

The velocity model is intended to provide the 3D crustal structure in the region at multiple length scales for seismic wave propagation simulations, both broadband ground motion and more localized shallow site response analyses. Therefore numerous sources of data are required to adequately constrain the model at different depths and length scales of interest. Figure 2 shows the distribution of numerous data sets across the Canterbury region used for the velocity model. Water wells, surface wave testing and geotechnical investigations constrain the shallow depths of the model (generally Quaternary materials) while seismic reflection surveys and petroleum wells constrain the moderate to large depths (generally pre-Quaternary materials). Basement geophysical properties are constrained by regional tomography data (Eberhart-Phillips et al. 2010) not shown in Figure 2.

3 PRE-QUATERNARY GEOLOGIC SURFACES

The characterisation and representation of the deeper, pre-Quaternary geology is a significant component of the velocity model. The deeper geology corresponds to the stratigraphy between the Quaternary geology and geologic basement (as shown in Figure 1). As with the Quaternary geology, the horizons between geologic units are capable of producing large velocity contrasts due to their depositional history and different material properties.

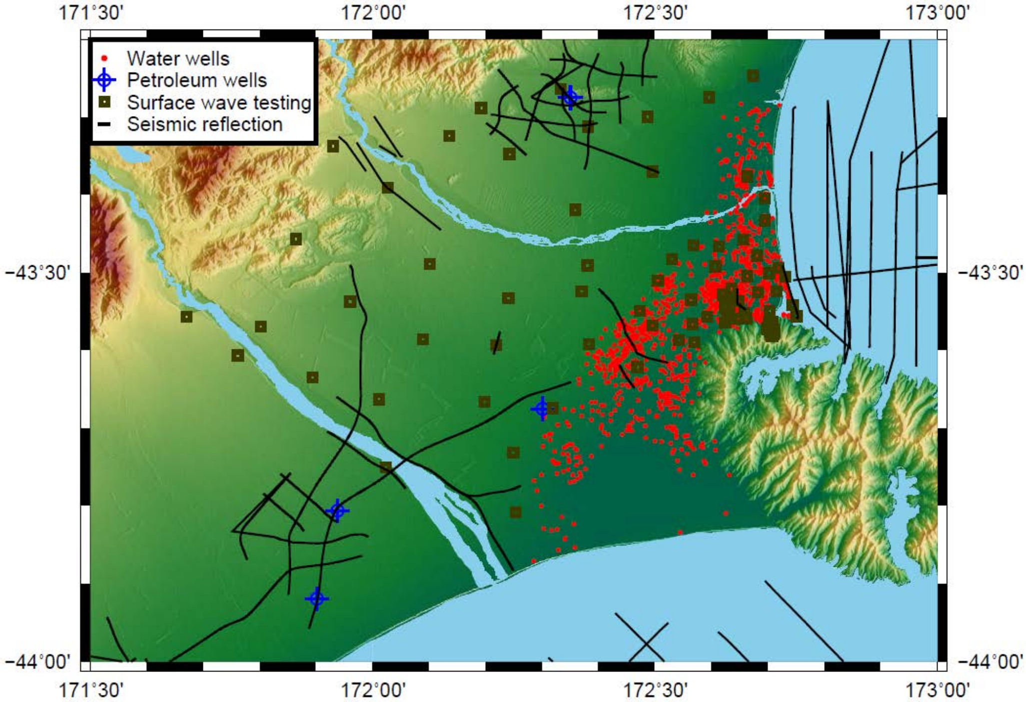

Figure 2. Data sources used in the development of the Canterbury Velocity Model (CVM).

The primary constraint for the pre-Quaternary geology is a dense and comprehensive network of seismic reflection surveys, shown in Figure 3 (as well as Fig. 2), originating from seven different campaigns over the past 50 years; primarily for petroleum exploration and post-earthquake reconnaissance (Pettinga et al., pers comm; Barnes et al. 2011; Dorn et al. 2010; Schlumberger Geco-Prakla 1998, 1999, 2000). The majority of the seismic reflection lines have been reinterpreted due to recent developments providing better understanding and constraints than in previous interpretations. This has resulted in better identification and consistency of critical seismic facies representing important lithological changes. The depth conversion of the reflection lines has been carried out with two way travel times (TWTT) velocities that were principally constrained by petrol well logs, and migration velocities. Both onshore and offshore seismic reflection lines are used to constrain the deeper geology of the velocity model to ensure a consistent and representative model across the entire model domain. The Barnes et al. (2011) lines in the Pegasus basin and SIGHT lines (University of Texas Institute for Geophysics, UTIG) in the South Canterbury basin constrain the offshore areas. The IndoPacific (IP) (Schlumberger Geco-Prakla, 1998, 1999, 2000) lines, Pettinga et al. (pers comm) and Dorn et al. (2010) lines are used to constrain the onshore areas. The reflection lines were complimented with other constraints such as petroleum industry drill holes, documented geologic outcrops and cross sections. Based on these constraints, regression Kriging was utilized to produce the geologic surfaces over the model domain.

Figure 4 illustrates, as an example of the several pre-Quaternary surfaces, a contour plot of the basement surface (elevation relative to mean sea level) along with the reflection lines used in the kriging process and a digital elevation model for areas where basement is considered as outcropping. This plot illustrates many features characteristic of the geologic basement. The Banks Peninsula region has a pronounced local high which is a consequence of the historic volcanic activity. The saddle structure between Darfield and Rolleston is produced as a geologic consequence of the local high at Banks Peninsula and the outcrop at the foot of the Southern Alps. Along the Southern Alps range front there are steep gradients present which correspond to extensive faulting, such as the Hororata fault and Montalto fault. The contour plot also explicitly highlights the Rakaia and Pegasus sedimentary basins to the south and east of Darfield, respectively, which are well constrained from reflection lines. The Pegasus basin, in particular, consists of a very complex structure due to severe offshore faulting. It is highly likely that the complexity seen in regions of high constraint also exists elsewhere in the Canterbury plains, but in the absence of direct physical constraints the adopted surfaces provide a relatively smooth surface.

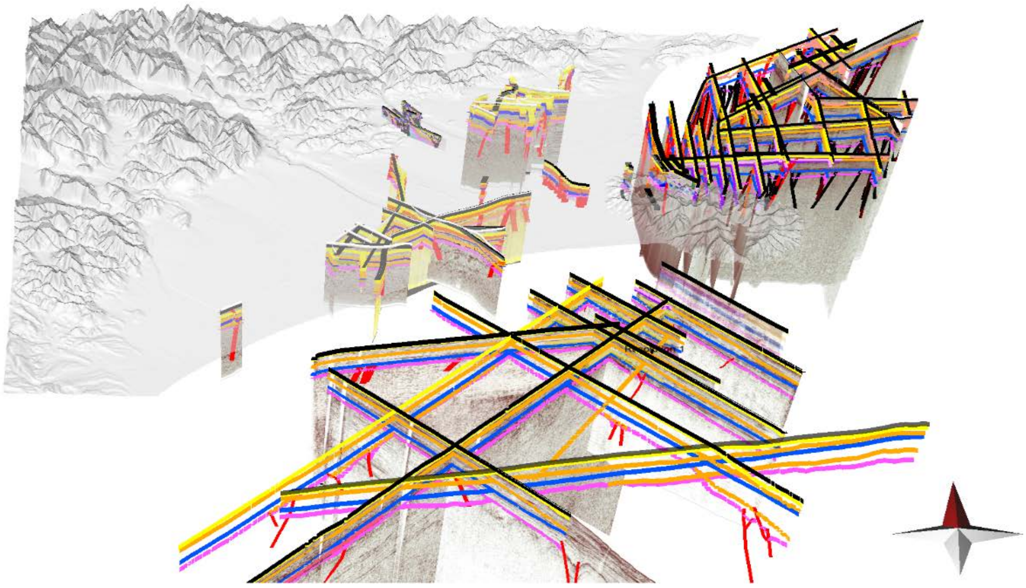

Figure 3. Perspective view of interpreted seismic reflection lines used in the development of deeper geologic surfaces.

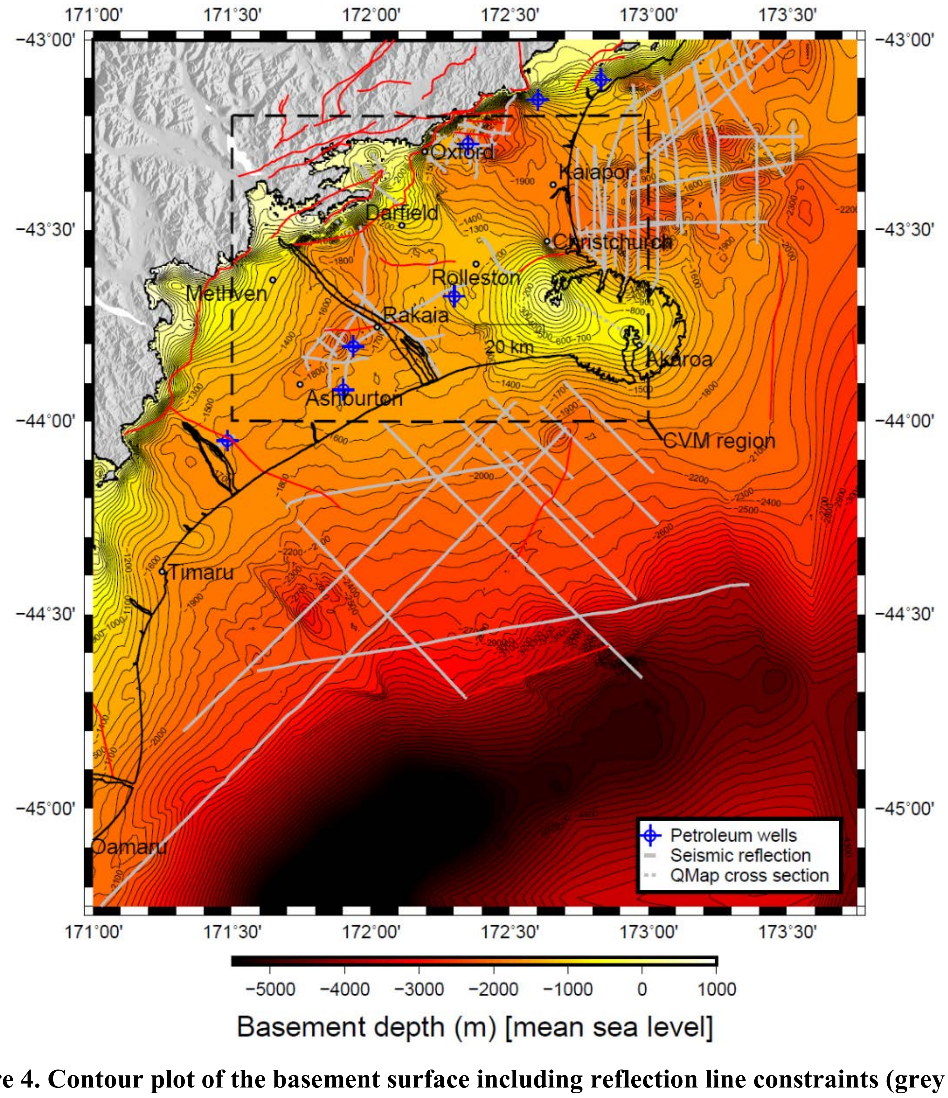

Figure 4. Contour plot of the basement surface including reflection line constraints (grey lines). Outcropped areas are shown as existing topography in the form of a digital elevation model.

4 QUATERNARY GEOLOGIC SURFACES

As already noted, the detailed representation and characterisation of the Quaternary units (as shown in Fig. 1), is a major component of this velocity model. The horizons between these Quaternary units often produce large velocity contrasts due to material and depositional differences, which are capable of significantly altering seismic waves, and leading to numerous wave phenomena relevant to the Canterbury earthquake sequence such as basin effects and nonlinear soil behaviour.

Over 1700 water well logs (as shown in Fig. 2) from Environment Canterbury (ECan) across the Canterbury region were the primary constraints used in the development of the Quaternary surfaces. The well log data were inspected, and lower quality logs removed, to obtain depths to the aforementioned Quaternary horizons at numerous locations. Information of maximum inland extents of paleo-coastlines were utilized to specify the domain of which inter-bedded (marine and terrestrial) Quaternary units were expected (red boundary in Figure 5). To the west of this inter-bedded region, the Quaternary is generally gravel dominated, and a single (undifferentiated gravels) geologic unit is sufficient.

Figure 5 shows the seven Quaternary surfaces which are recognised to comprise the top ~150m of surficial sediments below the urban Christchurch area. The complex, inter-bedded (gravels, sands, silts, organics etc.) stratigraphy near the coastline which has resulted from fluvial deposition from the mountains and marine regression and transgression due to sea level changes which occurred in the Quaternary age can be seen. Figure 6 provides an illustration of the thickness of the Christchurch and Springston Formations (i.e. depth from the ground surface to the top of the Riccarton Gravels). This figure illustrates the detailed representation of the spatial variation in unit thicknesses, with the numerous marine formations generally increasing in thickness on the eastern, coastal sides, and tapering to zero thickness on the western side at their maximum inland extents.

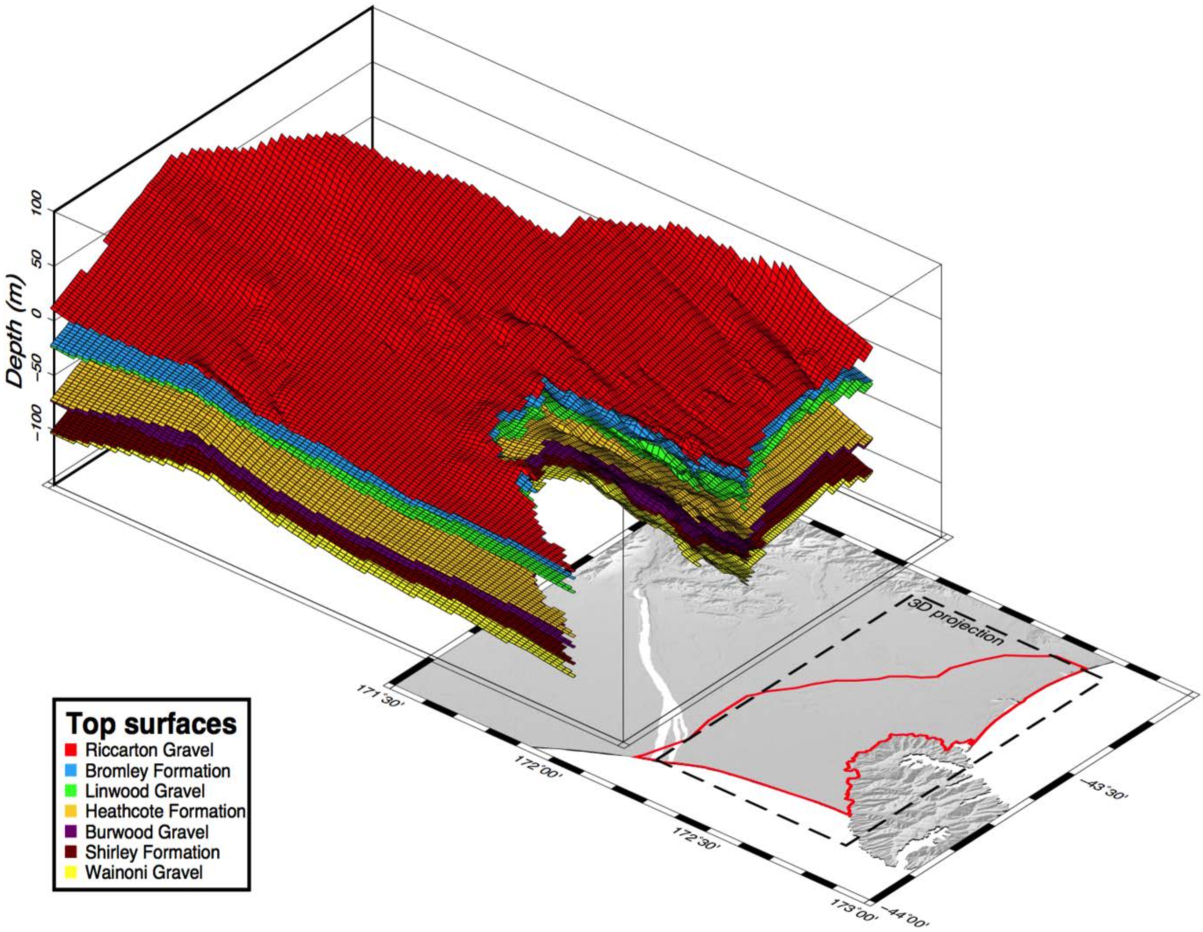

Figure 5. Geologic surfaces of the inter-bedded Quaternary structure beneath Christchurch (Surfaces correspond to the red outlined area).

Within the Quaternary surfaces, the younger surfaces are better constrained as more wells penetrate their respective horizons. Thus the top of the Riccarton Gravels horizon is the most well constrained of the Quaternary surfaces, with over 1500 wells penetrating its top, while the top of the Wainoni Gravels surface is the least well constrained with only 222 wells penetrating its top. There is little constraint and documentation of the Quaternary stratigraphy and structure below the Wainoni gravels which results in the top of the Wainoni gravels being the deepest of the Quaternary surfaces explicitly modelled. The Quaternary structure below the Wainoni Gravels is consequently categorized as undifferentiated gravels.

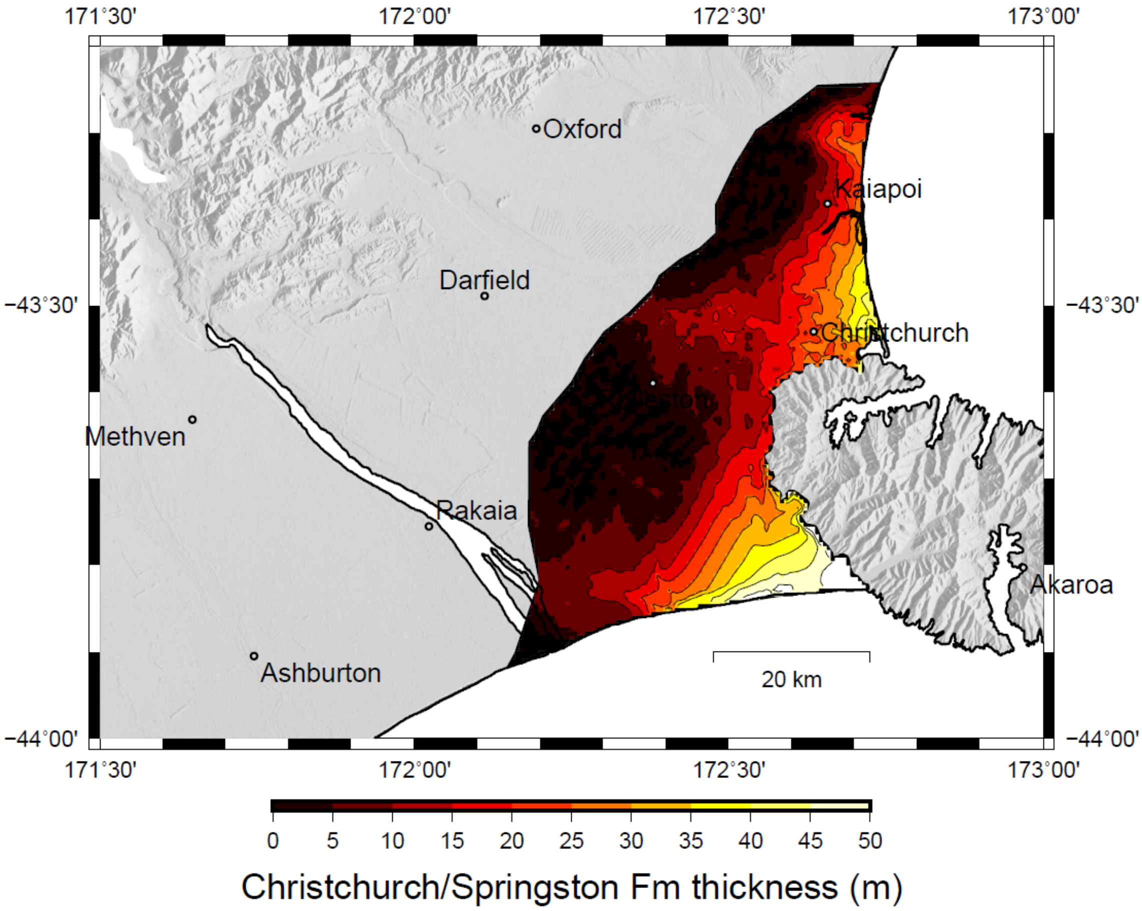

Figure 6. Contour plot of the Christchurch and Springston Formations thickness.

5 SEISMIC VELOCITIES

The prescription of seismic velocities is also a significant component of the velocity model. Currently, five different datasets are utilized for representing seismic velocities within each of the various geologic surfaces. The basement properties are controlled by 3D regional tomographic data (Eberhart-Phillips et al. 2010). P-wave velocities in all geologic units were obtained from seismic reflection profiles via a combination of: (1) sonic well logs; (2) reflection stacking velocities; and (3) the combination of well lithology and interpreted reflection TWTT's where sonic logs and stacking velocities were not available or documented (principally for older wells/profiles).

In deep (z>1km) geologic units, S-wave velocity is obtained from the empirical correlation of Brocher (2005). This correlation was validated for New Zealand conditions based on the 3D tomographic model data of Eberhart-Phillips et al. (2010). The density-P-wave velocity correlation of Brocher (2005) is also adopted throughout the model domain. In shallow (z<1km) geologic units, V_s is obtained directly from shear wave profiles derived from forward modelling of active- and passive-wave data (Cox et al. 2013). Active data includes that obtained with the United States National Science Foundation's (NSF) TRex vibroseis. The Quaternary surfaces (Fig. 5) were utilized as depth constraints in the velocity inversion of surface wave dispersion data.

For the near-surface Springston and Christchurch Formations in the Christchurch urban area (z<50m), high-spatial resolution seismic velocities (including V_{s30}) were obtained from over 13,000 cone penetration tests combined with a recently developed CPT-V_s correlation. Figure 7 illustrates the V_{s30} model which was derived from this CPT-based dataset (McGann et al. 2015).

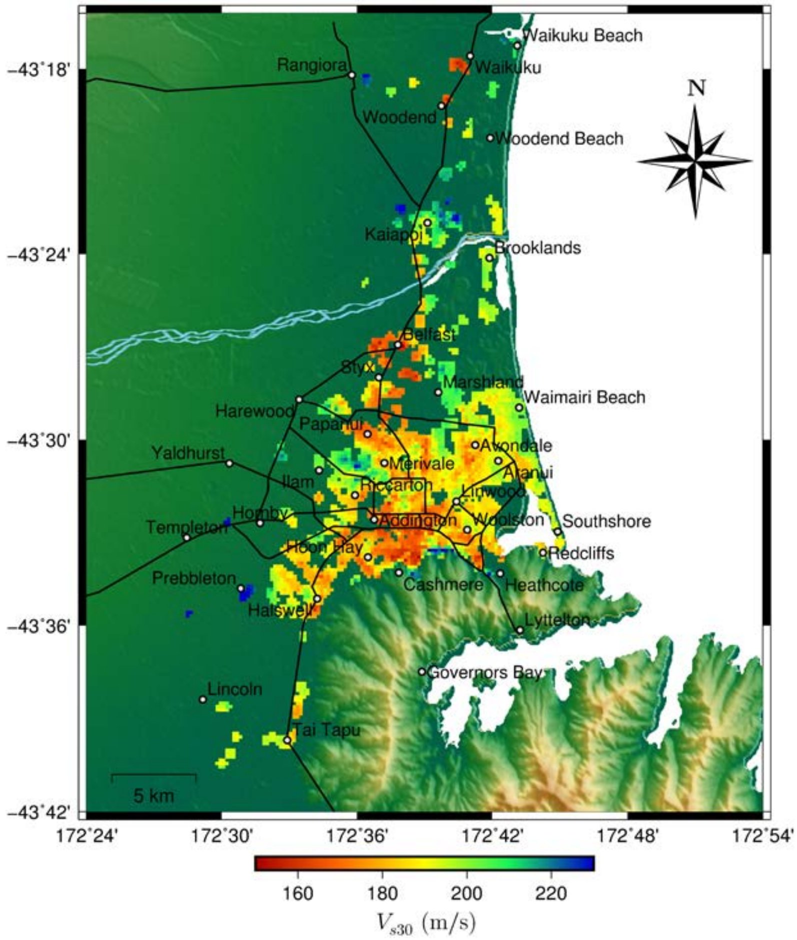

Figure 7. V_{s30} model based on over 13,000 CPT logs (after McGann et al. 2015).

6 CONCLUSION

A seismic velocity model of the Canterbury region was developed based on 3D geologic surfaces and velocities. The model follows a rule-based approach which prescribes P- and S-wave velocities, and density values to a point in 3D space from the appropriate data set depending on which geologic surfaces the point lies between. Data sets such as regional seismic tomography, seismic reflection surveys, well logs and shear wave profiles from surface wave analysis were employed to ensure that the velocity model represents the critical aspects of the crustal structure of the region. Numerous geologic surfaces have been produced, with particular attention given to the detailed characterization of the interbedded Quaternary geologic structure. The 3D seismic velocity model of the Canterbury region will enable synthetic ground motions to be computed using hybrid broadband ground motion simulations and site response analyses which will provide a means to understand the salient physical processes which resulted in the ground motions observed in the 2010-2011 earthquakes as well as predict future seismic scenarios of interest in this region.

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